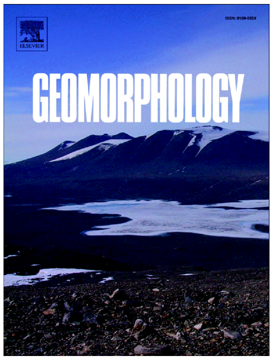

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Cross-cutting palaeo-ice streams in NE-Iceland reveal shifting Iceland Ice Sheet dynamics

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Abstract

Ice streams are thought to have regulated the past Iceland Ice Sheet (IIS) during and following the Last Glacial Maximum (LGM) by discharging ice and sediment from the interior of the ice sheet towards the shelf edge. Previous assessments of ice streams within the IIS have produced contradictory reconstructions of ice sheet dynamics and location of ice divides. Here, we reconstruct palaeo-ice streams in NE-Iceland based on detailed mapping of streamlined subglacial bedforms (SSBs) and other glacial lineations. The morphometrics, distribution and orientation of the SSBs indicate the flow-sets of several cross-cutting palaeo-ice streams and the location and migration of ice divides, while high density and packing of SSBs possibly suggest the axial zones of the ice streams. North-trending flow-sets suggest that during maximum glaciation and ice-sheet thickness, ice flow within the study area was largely unaffected by underlying topography allowing ice to flow northwards across valleys and fjords. This ice flow direction correlates with the orientation of previously identified troughs on the north-eastern shelf and indicates that an E-W orientated ice divide was located to the south of the study area. During deglaciation and ice sheet thinning, a N-S orientated ice divide was located to the west of the study area, and palaeo-ice streams became confined to valleys and fjords, so that associated flow-sets crosscut the older ones. The absolute ages of these flow-sets are uncertain, but the simplest interpretation is that the older ones

pertain to the LGM and the younger ones to the following deglaciation. This study sheds light on the dynamics and evolution of palaeo-ice streams within the IIS and highlights the importance of further efforts to understand the subglacial processes responsible for the formation of the streamlined subglacial bedforms as well as to constrain the evolution of shelf glaciation and chronology of ice stream retreat.

1. Introduction

Ice streams are corridors of fast-flowing ice that have long been recognized as the main regulators of ice sheet discharge and sediment flux (e.g. Bennett, 2003; Briner, 2016; Eyles and Ross, 2016; Stokes et al., 2016). Their vulnerability to climate and sea-level changes, their temporal behaviour, and mechanism of fast flow, are poorly understood (e.g. Bennett, 2003; Alley et al., 2004, 2005), and it is uncertain how ice stream drainage networks evolve and regulate rates of mass loss over longer timescales (Larter et al., 2019). Modern ice streams are present within the Antarctic and Greenland ice sheets (Bennett, 2003; Alley et al., 2004) and palaeo-ice stream landsystems have been reported from former ice sheets (Stokes and Clark, 2001). Their geomorphological imprint is characterized by streamlined terrain consisting of highly elongated drumlins or mega-scale glacial lineations (MSGL), geomorphologically heterogeneous onset zones, and abrupt shear margins to more sluggish ice (e.g. Briner, 2007; De Angelis and Kleman, 2008; King et al., 2009; Margold et al., 2015; Stokes, 2018). Ice streams are thought to have regulated the Iceland Ice Sheet (IIS) during and following the Last Glacial Maximum (LGM) by discharging ice and sediment from the ice sheet interior towards the shelf edge (Bourgeois et al., 2000; Stokes and Clark, 2001; Norðdahl and Pétursson, 2005; Hubbard et al., 2006; Spagnolo and Clark, 2009; Clark and Spagnolo, 2016; Patton et al., 2017). The location of ice streams within the IIS has been projected on the basis of large-scale topography, streamlined subglacial bedforms and glacial striae, often resulting in contradictory reconstructions of ice divides (Bourgeois et al., 2000; Hubbard et al., 2006; Fig. 1A). Norðdahl (1991) depicted major ice streams in the main fjords of central North Iceland whereas Bourgeois et al. (2000) reconstructed flow patterns across entire Iceland with topographic ice streams located in all major fjords, and ice divides over mountainous regions in between these fjords. Spagnolo and Clark (2009) concluded that major troughs and streamlined ridges on the Iceland shelf were imprints of palaeo-ice streams, and Clark and Spagnolo (2016) identified cross-cutting troughs indicative of multiple phases of shelf glaciation (Fig. 1A). A significant step in the study of palaeo-ice streams in Iceland was made by Principato et al. (2016) who mapped and quantified the properties of streamlined subglacial bedforms with spatial analysis, supporting the presence of palaeo-ice streams in NW-Iceland. Despite these important previous efforts, the configuration and cross-cutting relationships of palaeo-ice streams in Iceland are still relatively poorly understood, compared to many other regions that were occupied by past ice streams (e.g. Kjær et al., 2003; Greenwood and Clark, 2009a; Margold et al., 2015).

Our aim is to clarify the configuration, dynamics, and geomorphological imprint of palaeo-ice streams in NE-Iceland by mapping and analysing streamlined subglacial bedforms (SSBs) in the Þistilfjörður, Bakkaflói, Bakkaheiði, Vopnafjörður, and Jökuldalsheiði areas (Figs. 1 and 2). Previous studies of glacial history in this region are rare and have mainly focused on the last deglaciation and associated shoreline displacement after the Younger Dryas (YD) (Norðdahl and Hjort, 1993; Sæmundsson, 1995; Richardsson, 1997; Norðdahl et al., 2019). Patton et al. (2017) modelled a rapid marine deglaciation in this region from 21.8-15 ka BP (GS-2c throughout GS-2a[1]) with rates of mass loss comparable to the contemporary West Antarctic Ice Sheet (WAIS) (Hugonnet et al., 2021). According to their model, abrupt warming during the Bølling Interstadial (14.7-14.1 ka BP; GI-1e[1]) forced a dramatic collapse of the IIS onshore, consistent with what had been previously suggested by Ingólfsson and Norðdahl (2001) and Norðdahl and Ingólfsson (2015). Patton et al. (2017) modelling suggests that this collapse was analogous to contemporary rates of mass loss in Greenland and the Amundsen Basin in the WAIS (Rignot et al., 2011; Feldmann and Levermann, 2015; Hugonnet et al., 2021), with the coastal areas of NE-Iceland ice free from c. 17 ka BP. According to their model, the ice margin retreated far inland at 13.2 ka BP but readvanced to the coast in Vopnafjörður, but not elsewhere in this region, at 11.7

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[1] According to Lowe et al. (2008).

ka BP (YD; GS-1[1]). Norðdahl et al. (2019) studied the glacial history of Fljótsdalshérað (Fig. 2A) and concluded that it was occupied by a fast-flowing ice stream during the LGM, and deglaciated between 14.7 and 13.2 cal. ka BP at the earliest.

2. Setting

The study area covers the northeastern part of Iceland, from Þistilfjörður in the north to Vopnafjörður and Jökuldalsheiði in the south (Fig. 1). The bedrock in this region consists primarily of Miocene and Pliocene (>3.3-0.8 myr) plateau basalts with intercalated sediment horizons. It generally becomes progressively younger towards the west. In general, the basalts have a northward strike and are heavily intersected by N-S trending dykes, especially in the Bakkaheiði area (Sæmundsson, 1977; Jóhannesson and Sæmundsson, 2009). The study area is delineated to the west by an arcuate chain of Middle Pliocene (0.12-0.8 Ma) hyaloclastite ridges that stretch from the Vatnajökull ice cap in the south towards the northern coast and separate the area from the currently active northern volcanic rift zone (Fig. 2; Hjartardóttir et al., 2010; Hjartarson and Sæmundsson, 2014). Hence, basal ice flow within the study area was not directly affected by volcanic activity and glacial landforms are not obscured by post-glacial lavas. To the south and southeast, the study area is delimited by the deep channel/valley of the Jökulsá á Brú glacial river and the Smjörfjöll Hellisheiði massif. The analysis of SSBs is focused on the three, major valley-fjord systems that dominate the coastal areas, and associated uplands and plateaus to the south or south-west of these systems (Fig. 2A). These valley-fjord systems are the result of frequent glaciations since the onset of the Quaternary (Benediktsson et al., 2021a). Þistilfjörður is the widest valley (~18-33 km) whereas the Vopnafjörður catchment is characterized by three narrow valleys (~1-6 km), which are carved into the highland plateau. The Bakkaflói area in between comprises restricted lowlands, shallower valleys, and lower plateaus. These areas exhibit glacially streamlined terrain with bedforms that have not been previously mapped, although glacial striations are indicated on older maps (Sæmundsson, 1977).

Besides, Patton et al. (2017) presented a rough estimate of a flow set extending from Jökuldalsheiði in the highlands to the coast in Vopnafjörður (Fig. 1B).

3. Methods

The principal data source used for mapping and analyzing the SSBs was the Arctic Digital Elevation Model (ArcticDEM) with a 2 m vertical and <1 m horizontal resolution (Porter et al., 2018). The data has been corrected and mosaicked by the National Land Survey of Iceland (NLSI), the Icelandic Met Office, and the Polar Geospatial Center (Porter et al., 2018). Additionally, infrared Spot satellite images with 2.5 m resolution from NLSI and aerial images from Loftmyndir ehf., were used to facilitate the mapping. The mapping was ground verified by field checking selected areas within the study area.

Geomorphological mapping of the SSBs was undertaken following the guidelines of Chandler et al. (2018), by combining the interpretation of remotely sensed data and field data. Analysis of the data and mapping was conducted in ESRI ArcGIS 10.4 and finalized in Canvas X. The identification and mapping of the SSBs were carried out at a scale of 1:3000. All data were handled in the Lambert Conformal Conic reference system, and elevations are in meters above sea level. Hillshaded relief models of the ArcticDEM were produced and used as a basis for the mapping. To avoid azimuth bias (Smith and Clark, 2005; Smith and Wise, 2007), the hillshades were illuminated from four different azimuths, 0°, 45°, 90° and 315°, selected according to the orientation of the bedforms, and one with the solar angle at 90° (i.e. overhead). The hillshades were vertically exaggerated by three to five with a solar angle of 25° to enhance subtle features. A slope map and 2-m contour lines were generated from the ArcticDEM to help delineating the bedforms. To minimize the influence of user bias, strict criteria were followed during the mapping (Smith and Clark, 2005; Hillier et al., 2015). For SSBs to be mapped, they had to show a clear orientation of elongation, be upstanding from the landscape in both axes, and have a clear break of slope. Mapping was therefore carried out using a combination of the hillshades with different azimuths, satellite and aerial images, slope map and contour lines. A polygon was drawn at the break of slope of each bedform. Although automated mapping techniques are increasingly being applied in glacial geomorphology, especially in areas with large numbers of similar features (>1000 to >10,000; Yu et al., 2015; Sookhan et al., 2016; Chandler et al., 2018), the bedforms here were manually digitized due to the geospatial resolution and the relatively small number (<800). The SSBs are classified into drumlins and mega-scale glacial lineation (MSGL), with the latter having elongation ratios of >10:1 (Stokes and Clark, 1999). We do however acknowledge that drumlins and MSGLs are a part of a morphological continuum and that this strict boundary is up for debate (Spagnolo et al., 2014; Ely et al., 2016). Therefore, in figures 3, 5 and 6, drumlins with elongation ratios <5:1 and 5-10:1 are separated for better visualization of the E.R. spectrum. If bedforms could not be delineated due to undiscernible break of slope but streamlining of the landscape was nonetheless clear, polylines were used to indicate the streamlining and mapped as glacial lineations. Despite the possibility that the streamlining of bedrock with negligible till cover may be the cumulative result of several ice sheet cycles (Hughes et al., 2010), we include streamlined bedrock in our mapping because of the difficulty in distinguishing separate glacial cycles in such areas.

To investigate the morphology of the SSBs, the length of the long axis, the width orthogonal to the long axis and the orientation of the long axis were measured for each bedform using the minimum bounding geometry tool in ArcGIS, as described by Napieralski and Nalepa (2010), although other approaches may also be useful depending on the bedforms' planar shape and elongation ratio (Jorge and Brennand, 2017). The elongation ratio (E.R.) is found by dividing the length with the width. The orientation of the bedforms was compiled in rose diagrams for each selected subarea. A point was created in the center of each bedform and the density calculated by counting the number of bedforms within each 4 km^2 grid cell. The packing of bedforms, i.e. the surface area of bedforms per 4 km^2, was calculated with the Point Density tool in ArcToolbox with bedform area as the population field. This cell size turned out to be the most effective one for visualizing bedform density and packing considering both bedform dimensions and map scale, similar to other studies (e.g. Rice et al., 2020).

4. Results

Streamlined subglacial bedforms (SSBs) and glacial lineations in NE-Iceland are distributed within the Þistilfjörður, Bakkaflói and Vopnafjörður fjord-valley systems and associated plateaus, such as Jökuldalsheiði and Bakkaheiði (Fig. 2A). The SSBs are more abundant on the highland plateaus (above ~400 m a.s.l.) and elevated terrain near the coast (above ~200 m a.s.l.), except in Þistilfjörður where they mainly occur in the lowlands below 300-400 m a.s.l. (Fig. 2B). Mapping revealed 797 SSBs within the entire study area, as well as additional 417 glacial lineations, which were mapped to further indicate palaeo-ice flow direction.

4.1 Þistilfjörður

The Þistilfjörður area is characterized by sparse and generally widely spaced SSBs (n=164) and glacial lineations, with 7% (n=12) classifying as MSGLs (Fig. 3A). Although the range in SSB length stretches from 101 m to 2694 m, the median is 576 m while the mean is 717 m (Table 1). Shorter landforms are mainly focused on the coastal, western, and southern parts whereas longer and more elongate landforms are concentrated in the eastern part where glacial lineations, drumlins and MSGLs are juxtaposed (Fig. 3A). The width of the SSBs has a median of 151 m (range:36-942 m) a, and the median elongation ratio is 3.2:1 (range: 1.9:1-16.8:1; Table 1). In the southeastern part of this area, a complicated network of hummocky and transverse ridges appears to superimpose highly elongate SSBs, presumably MSGLs, which are thus very difficult to map. Many of these highly elongate bedforms underlying the hummocky and transverse ridges appear to be segmented (Fig. 3B-D). The SSBs show a mean orientation of 23° (SSW-NNE) (Fig. 3A; Table 1). Most of the largest bedforms in Þistilfjörður appear to be streamlined bedrock hills.

4.2 Þistilfjörður-Bakkaflói transition zone

On the eastern margin of the Þistilfjörður area, a transition to the Bakkaflói area occurs within a 2.5-4.5 km wide zone. This zone is morphologically complicated but seems to comprise ribbed moraine with individual ridges of various orientation and highly streamlined but segmented glacial bedforms with S-N orientation. These segmented bedforms appear to be superimposed by generally SW-NE orientated SSBs and lineations pertaining to the Bakkaflói area (Fig. 4). This superimposition is indicated by some of the S-N orientated bedforms (black lines and polygons on Fig. 4) in that the sediment within them appears to be smeared-out towards the northeast. Sediments within SW-NE orientated bedforms do not seem to be smeared out in the same way to the north. Thus, these cross-cutting relationships suggest that ice flow in this area was initially towards the north and subsequently towards the north-east (Fig. 4). Unfortunately, suitable bedrock outcrops containing striations that could potentially verify these crosscutting relationships are absent in this area. However, about 5 km north of this area, striations with an orientation towards the north have been reported (Sæmundsson, 1977; Norðdahl and Hjort, 1993).

4.3 Bakkaflói area

In the Bakkaflói area, the main cluster of SSBs and glacial lineations occurs within a relatively well-developed drumlin field that is located on the Kverkártunga plateau between two shallow valleys (Fig. 5A). Several similar features occur just to the south, east, and north of this plateau. A total of 77 SSBs were mapped within the Bakkaflói area. Their length and width are rather uniform; the length has a median of 451 m (range:135-1095 m) , and the width a median of 154 m (range: from 61-347 m). The median elongation ratio of the SSBs in the Bakkaflói area is 2.9:1, within a range of 1.9:1-8.3:1 (Table 1). The SSBs and glacial lineations in this area are mainly orientated SW-NE (35°) (Fig. 5A, E-F), although a few in the southern part of this area are orientated N-S suggesting a curvature in the former ice flow direction within this area (Fig. 5A).

4.4 The Bakkaheiði plateau

The Bakkaheiði plateau reveals a dense population (n=246) of closely spaced drumlins, MSGLs and glacial lineations that are orientated S-N (Fig. 5A. Only about 4% (n=9) of the SSBs classify as MSGL (Table 1). The median length, width, and elongation ratio of the SSBs on Bakkaheiði are 530 m (range:

154-3841 m), 147 m (range: 51-459 m), and 3.6:1 (range: 2-14.4:1), respectively, with the longest bedform being nearly 4 km long and a maximum elongation ratio of 14.4 (Table 1). The Bakkaheiði population has an abrupt boundary to the west where SSBs and glacial lineations become totally absent above 750 m a.s.l. (Fig. 2B), and to the south where it appears to be truncated by SW-NE orientated bedforms and lineations pertaining to the Vopnafjörður system (Fig. 5A). The bedrock strata in Bakkaheiði mainly have a southward strike (dip towards west) along a monoclinic flexure zone, although an opposite strike and dip also occurs just east of this zone (Icelandic Institute of Natural History, 2019). These strata frequently crop out on the surface in the form of low, elongate bedrock ridges. Thus, glacial lineations and streamlined bedforms with a bedrock core are common and occur juxtaposed with sedimentary bedforms (Fig. 5B-C). The bedrock crops out in a few places but tends to be much weathered; hence, striations are rare but those reported have an orientation towards the NNE (Sæmundsson, 1977; Norðdahl and Pétursson, 2005).

4.5 The Vopnafjörður-Jökuldalsheiði area

The Vopnafjörður system just south of Bakkaheiði includes three SW-NE orientated valleys in the outer part and the Jökuldalsheiði plateau that stretches southwards into the highlands north of the present Vatnajökull ice cap (Figs. 1 and 2). Collectively, this system contains a total of 310 SSBs with a median length of 749 m (range: 200-2505 m), median width of 192 m (range: 43-666 m), and elongation ratios with a median of 3.7 (range 1.9:1-12.8:1) (Table 1). A large majority of these bedforms classify as drumlins (~96%) as only a few MSGLs were observed (n=11) (Fig. 6A). In the outer part of the valleys, elevated bedrock separating the three valleys contains glacial lineations with predominantly S-N orientation, which correlates with the SSBs on Bakkaheiði and indicates an older palaeo-ice flow direction towards the north. On the Bustarfell and Tunguheiði plateaus, dense clusters of sedimentary drumlins form well-defined drumlin fields with rather consistent drumlin sizes and shapes (Fig. 6A-F). These drumlins are often cross-cut by transverse channels that may be of ice-marginal origin (Fig. B-C). Bedforms on the Jökuldalsheiði plateau are rather sparse and have more variable morphometrics (Fig.

6A). The bedforms within the Vopnafjörður system reveal a converging pattern with variable orientations in the highlands but largely parallel the trend of the fjord-valley in the central part with more constant SW-NE orientations (Fig. 6A). This is consistent with the orientation of a few striations previously reported from this area (Sæmundsson, 1995; Norðdahl and Pétursson, 2005). On the northern side of this system, near the mouth of the fjord, this orientation clearly crosscuts the N-S orientation of the bedforms within the Bakkaheiði subarea (Fig. 6A), indicating that ice flow within the Vopnafjörður system may have been active for a longer period.

4.6 Statistics of the streamlined subglacial bedforms

In total, 797 SSBs and 417 glacial lineations have been identified and mapped in our study area in NE-Iceland. For the SSBs identified, 765 (96%) classify as drumlins and 32 (4%) as MSGL. The morphometrics are summarized in Table 1 and illustrated with histograms on Fig. 7. Collectively for all the bedforms, the median length is 623 m with a range of 101-3841 m (mode: 300-500 m), and the median width is 163 m with a range of 36-942 m (mode: 100-150 m). The median elongation ratio for the entire dataset is 3.5:1 with a range of 1.9:1-16.8:1 (mode: 3:1-4:1). For drumlins and MSGLs separately, the mean elongation ratios are 3.8:1 and 11.7:1, respectively. The histograms all demonstrate a unimodal distribution with positive skews, similar to other studies of SSBs morphometrics in both Pleistocene and modern glacial environments (e.g. Clark et al., 2009; Stokes et al., 2013; Principato et al., 2016; Benediktsson et al., 2016; Hillier et al., 2018), and the box plots show that 50% of the bedforms are between 414-915 m long, 119-225 m wide and with an elongation ratio between 2.9-4.7:1 (Fig. 7). This also suggests that the dimensions at which drumlin formation is initiated are seldom below the 100 m magnitude, which may imply that few small bedforms are generated (Hillier et al., 2018). A linear regression between length and width reveals a moderately strong relationship between these two variables (r^2=0.47) with less than half of the variance in width explained by the variance in length (Fig. 8A). This may reflect a variable degree of bedform maturity, influenced by residence time beneath the ice (duration of ice flow), but moreover indicates that the length-to-width ratio is also influenced by other factors, such as substrate structure and composition, and subglacial hydrological and glaciological processes (Clark et al., 2009; Benediktsson et al., 2016). The linear regression between the length and elongation ratio reveals a weak relationship (r^2= 0.27) with less than a third of the variance in elongation ratio explained by the variance in length, (Fig. 8B). In contrast, a linear relationship between width and elongation ratio is not identified although the plot on Fig. 8C demonstrates that the largest elongation ratios (from ~8:1 to 16.8:1) occur for the narrowest bedforms and that the far widest bedforms have low elongation ratios (Fig. 8C). These morphometrics suggest that the SSBs in NE-Iceland comprise a continuum from stubby bedforms to highly elongated bedforms as the low- and high-end members, respectively (Ely et al., 2016). Bedforms with an elongation ratio >10 classify as MSGLs and represent only 4% of the dataset (n=32; Table 1), which is somewhat lower than reported from NW Iceland (Principato et al., 2016). The MSGL are most frequent on the Bakkaheiði plateau, in the eastern part of Þistilfjörður, and on the plateaus and slopes above the Vopnafjörður valleys (Figs. 2, 3, 5, 6).

Analysis of the density and packing of the SSBs reveals that bedforms are most scattered in Þistilfjörður and Jökuldalsheiði and most clustered in specific areas of Bakkaflói, Bakkaheiði and Vopnafjörður where 4-9 SSBs per 4 km^2 grid cell is quite common. More specifically, the highest density of SSBs occurs within the drumlin fields of Bustarfell and Kverkártunga as well as on the Bakkaheiði plateau, where 7-9 and even up to 18 SSBs occur, respectively, per 4 km^2. These bedforms are all relatively small, which partly explains their high density (Fig. 9A). The packing of the SSBs shows similar pattern to the overall density, with prominent areas of high packing on plateaus and slopes above the Vopnafjörður valleys as well as on the Bakkaheiði plateau (Fig. 9B).

5. Discussion

5.1 SSB morphometry and implications for processes of formation

The morphometry of the SSBs within our study area is quite variable, which probably indicates diverse composition and internal structure, maturity, as well as subglacial processes responsible for their formation (Krüger, 1987; Clark et al., 2009; Stokes et al., 2011; Dowling et al., 2015). The mean length, width, and elongation ratio of our SSBs are similar to those of both Pleistocene (Clark et al., 2009; Dowling et al., 2015) and modern drumlin fields (Krüger, 1987; Jónsson et al., 2018; Hillier et al., 2018) indicating that the SSBs have been formed through the streamlining of pre-existing landscape and that few if any small drumlins are produced (Figs. 7 and 8). Our study area includes well-developed drumlin fields, such as in Kverkártunga, Bustarfell, and Tunguheiði, with SSBs of relatively uniform size and shape within each field (Figs. 5 and 6). This implies that the substrate from which the bedforms develop in these fields is rather homogenous and that the processes under which they formed were persistent (Dowling et al., 2015; Benediktsson et al., 2016; Iverson et al., 2017). Therefore, these areas may also be considered as indicating the axial zones of ice streaming where relatively high ice-flow velocities persisted for a long time, either during maximum glaciation or deglaciation, or both. Although the SSBs in these fields appear to be primarily sedimentary, it is difficult to determine exactly which subglacial processes contributed to their formation without data on their internal structure and composition. A potential suitable modern analogue exists at Múlajökull, Iceland, where drumlins of similar dimensions consist primarily of till layers and were formed through a combination of erosion and deposition during successive surge cycles (Johnson et al., 2010; Benediktsson et al., 2016). Controlled by the distribution of effective stress on the bed, net till aggradation over the entire bed during surging and net erosion on drumlin heads, flanks and inter-drumlin areas during quiescent flow caused the drumlins to grow rapidly in relief and elongation and migrate downglacier (Benediktsson et al., 2016; Iverson et al., 2017). If the drumlins within these drumlin fields in NE-Iceland were formed under fluctuating ice-flow velocities (e.g. periodic slow-down or shut-down), this model predicts that they consist of multiple till layers with unconfomities below the uppermost till at drumlin heads and flanks (Benediktsson et al., 2016; Iverson et al., 2017). In the absence of fast flow (surging), the drumlins would have formed through erosion only (Iverson et al., 2017), causing lowering of the bed and leaving no substantial stratigraphic record except a layer of deforming subglacial debris that eroded into antecedent sediments or bedrock (Eyles et al., 2016; Sookhan et al., 2016). This could possibly apply to the SSBs on Bakkaheiði, in Þistilfjörður and on Jökuldalsheiði that are apparently bedrock cored with a veneer of till. Consequently, it raises the question if these SSBs are formed initially under sluggish ice and if the erosion of the bed is a means to create a streamlined, low-friction surface that ultimately allows faster ice flow and ice streaming (Eyles et al., 2016). Additional studies of the SSBs in NE-Iceland should aim at deciphering their internal architecture and compositions in order to better determine which processes contributed to fast ice flow and the formation of the streamlined terrain.

5.2 Configuration and cross-cutting flow-sets of palaeo-ice streams

The mapped streamlined subglacial bedforms (SSBs) show a pattern that we interpret as different flow-sets of several palaeo-ice streams in NE-Iceland. The SSBs in Þistilfjörður suggest a slightly convergent flow from the highlands to the lowlands, indicating funneling of ice towards the Þistilfjörður fjord and trough beyond (Fig. 3A; Spagnolo and Clark, 2009). The SSBs and glacial lineations in this area are of variable dimensions from small and less elongated drumlins to large bedrock forms and highly elongated MSGLs. This possibly indicates different generations of SSBs and superimposed flow sets, which, however, share a common, dominant flow direction to the north during full glaciation and deglaciation phases and thus, do not reveal any obvious cross-cutting relationships. An exception to this occurs within a narrow zone at 150-250 m a.s.l. between the Þistilfjörður and Bakkaflói areas where subtle elongated and often segmented bedforms crosscut at almost right angles (Fig. 4). We interpret this as the superimposition of two different flow-sets: an older one with ice flow towards the north and a younger one with ice flow to the northeast and east off the elevated ground between the two areas. In the Bakkaflói and Bakkaheiði area, the SSBs clearly represent two generations of palaeo-ice streaming with the S-N orientated flow-set on the Bakkaheiði plateau pre-dating the SW-NE flow-set in Kverkártunga and adjacent areas in Bakkaflói (Figs. 5 and 10). The Bakkaheiði flow-set with SSBs orientated S-N also clearly pre-dates and is cross-cut by the SW-NE flow-set in Vopnafjörður (Figs. 2 and 5). Although some of the SSBs within the Bakkaheiði flow-set appear to be sedimentary in composition, most of them are bedrock-cored with a relatively thin sediment cover (Fig. 5B-C). This is also true for the southernmost part of this flow set on the narrow peninsula that extrudes from the coast in Vopnafjörður. Because the location, morphology, and formation of bedrock-cored SSBs along structural geological lineaments tend to be controlled by the bedrock characteristics (Newton et al., 2018), it is worth considering if the SSBs within this flow-set truly reflect the palaeo-ice stream flow direction or if they are merely a result of the attenuation of S-N orientated bedrock forms by obliquely overriding ice. Our data reveal no oblique superimposition by SSBs or remolding of bedrock lineaments in this area, as reported from many other palaeo-ice stream beds (e.g. Hughes et al., 2010; Evans et al., 2020), that could support cross-cutting flow-sets in this area. Consequently, we interpret the bedrock-cored SSBs within the Bakkaheiði flow-set as representing long-term, cumulative palaeo-ice streaming towards the north (Krabbendam et al., 2016). This resembles the Lögurinn-Úthérað lowland area 40-50 km southeast of Bakkaheiði (Fig. 2) where remolded bedrock, crag-and-tails, and drumlins parallel or sub-parallel the northward bedrock strike but nevertheless represent the flow direction of a palaeo-ice stream during the LGM and the deglaciation (Norðdahl et al., 2019).

The abrupt cross-cutting of the Bakkaheiði flow-set by the SW-NE orientated SSBs immediately to the south indicates the flow set of a relatively younger, northeastward flowing palaeo-ice stream in the Vopnafjörður area (Figs. 5 and 6). This flow-set extends far into the highlands north of the present Vatnajökull ice cap and includes S-N orientated SSBs on the Jökuldalsheiði plateau. Because of the variable dimensions of the SSBs in the Jökuldalsheiði area (upstream of the Vopnafjörður valleys and uplands), it is possible that they represent different generations of palaeo-ice streaming, as in the Þistilfjörður area, with the larger and smaller bedforms resulting from long-term and short-term fast ice flow, respectively (Clark et al., 2009; Benediktsson et al., 2016; Krabbendam et al., 2016; Hillier et al., 2018).

5.3 Palaeo-ice stream dynamics, flow directions and location of ice divides

The SSBs in our study area in NE-Iceland are most common at altitudes between 200 and 650 m a.s.l., signifying that they predominantly occur on upland plateaus rather than in the valleys (Fig. 2B). This is somewhat similar to NW-Iceland where Principato et al. (2016) mapped SSBs mainly above 300-400 m a.s.l., although they also identified indistinct glacial lineations at altitudes down to about 100 m a.s.l. in valleys. Highly streamlined bedforms identified by Bourgeois et al. (2000) in central north Iceland and later mapped by McKenzie et al. (2017) and Benediktsson et al. (2018) also occur mainly at 300-400 m a.s.l. For our study area in NE-Iceland, where the marine limit occurs at altitudes up to 65 m a.s.l. (Norðdahl and Hjort, 1993; Sæmundsson, 1995; Richardsson, 1997), we suggest that the shortage of SSBs at low altitudes indicates that they are, at least partly, obscured by younger marine and glaciofluvial sediments or have been eroded by post-glacial fluvial action. In contrast, the absence of SSBs above 750 m a.s.l. probably indicates low ice-flow velocities and/or a partly frozen bed at or near ice divides – conditions that are generally unfavorable for the formation of SSBs (e.g. Kleman and Hättestrand, 1999; De Angelis and Kleman, 2008; Atkins, 2013; Dubé-Loubert et al., 2021). The overall low density of SSBs at the higher altitudes compared to within ice-stream trunk flow zones (Figs. 2 and 9) also implies that the upper limit of SSB distribution occurs at the onsets of ice streaming (De Angelis and Kleman, 2008). This is consistent with the location of ribbed moraine areas in the uplands of Vopnafjörður that mainly occur upstream of dense SSBs and are considered suggestive of ice stream onsets (Helgadóttir, 2020). A series of transverse ridges in the Bakkaflói area is also tentatively interpreted as ribbed moraine representing a transition zone between slow-flowing ice near ice divides and fast-flowing ice within an ice stream (Benjamínsdóttir, 2021). Consequently, it may be deduced that a major ice divide was at some point located over the mountain range at the western limit of the study area and a minor one over the highland plateau between Þistilfjörður and Vopnafjörður. The latter may have been induced upon ice thinning during late deglaciation whereas the former may possibly have persisted since the early phase of deglaciation. This agrees with previous reconstructions of Lateglacial ice divides in this region based on striations with opposite orientations on the eastern and western side of the mountain range as well as in the highlands between Þistilfjörður and Vopnafjörður (Sæmundsson, 1977; Pétursson, 1991; Norðdahl and Hjort, 1993; Sæmundsson, 1995; Norðdahl and Pétursson, 2005).

The ice flow pattern depicted by the SSBs suggests that all palaeo-ice streams extended beyond the present coast and into troughs on the Iceland shelf, through which they probably reached the shelf edge during maximum glaciation (Spagnolo and Clark, 2009; Patton et al., 2017). The high density and packing of SSBs on Bakkaheiði and in Vopnafjörður (Fig. 9) may suggest that these areas contained the highest ice-flow velocities and acted as the axial zones of ice streaming and/or signify a mechanism of shutdown during separate phases of glaciation (Clark and Stokes, 2001). While the density and packing of SSBs is likely influenced by sediment availability in many areas, bedrock structure beneath a thin sediment cover may also play a role, as indicated by the bedrock-cored SSBs on Bakkaheiði where the bedrock strike parallels or sub-parallels the former ice-flow direction. Modelling experiments suggest that an E-W orientated central ice divide was stable at the time of maximum thickness during the LGM (~1500-2000 m) and throughout the entire glaciation (Patton et al., 2017). In the eastern part of Iceland, this ice divide was probably located near or above the present Vatnajökull ice cap (Bourgeois et al., 2000; Patton et al., 2017). Our data suggest that an ice stream may have flowed northwards from this ice divide and obliquely across but not along the Vopnafjörður valleys (Fig. 10A). This implies that the IIS was thick while this ice stream was active, and that ice flow was independent of underlying topography during maximum glaciation. Similar scenarios are well known from the interior of the Laurentide and Fennoscandian ice sheets, where thick ice streams crossed preglacial valleys (Ross et al., 2009; Putnins and Henriksen, 2017), and from Western Norway where LGM ice flow went right across deep valleys and fjords (Mangerud et al., 2019). Northward flow across the Vopnafjörður valleys conforms to the Bakkaheiði flow-set and implies that the S-N orientations observed on the southern part of the Jökuldalsheiði highland plateau and in the Þistilfjörður area could be the cumulative result of more than one generation of ice streaming (Hughes et al., 2010). Consequently, smaller, and less elongated SSBs would represent a more immature stage of development, possibly due to lower ice flow velocities or shorter duration of flow (Clark et al., 2009; Benediktsson et al., 2016; Iverson et al., 2017; Ely et al., 2018). Similarly, the size of SSBs within the well-defined drumlin fields of Kverkártunga, Bustarfell and Tunguheiði (see Figs. 2, 5, and 6 for locations) is rather uniform, which possibly implies that NE trending flow-sets in general are primarily a result of only one generation of ice streaming under relatively stable conditions – hence, a signature of deglaciation. In contrast, the larger variety of SSB morphometries within S-N orientated flow-sets results from a longer and more variable period of ice streaming from a maximum glaciation to deglaciation. By dating the timing of the formation of SSBs, this hypothesis could be tested. However, datable material within subglacial bedforms tends to be rare and thus, this may have to be tested with ice sheet modelling.

Upon ice thinning during deglaciation, ice stream flow directions became progressively more controlled by the underlying topography with a regional ice divide located over the N-S orientated mountain range (Þríhyrningsfjallgarður-Dimmifjallgarður) that delimits the study area to the west (Figs. 2 and 10B). Previous reconstructions of the IIS have also suggested a regional ice divide in this area either during the LGM (e.g. Bourgeois et al., 2000) or the following deglaciation (e.g. Norðdahl and Hjort, 1993). Local ice divides would also have formed over the Smjörfjöll-Hellisheiði massif and then progressively in elevated terrain between the different flow-sets, such as between Þistilfjörður and Bakkaflói as well as Þistilfjörður and Vopnafjörður (Fig. 10B), as the ice sheet continued to thin. Interestingly, Spagnolo and Clark (2009) and Clark and Spagnolo (2016) identified troughs on the northeastern shelf that overlap at different depths, i.e. a shallower one that is incised in a NNE direction and cross-cut by a deeper one orientated SW-NE. Clark and Spagnolo (2016) suggested these troughs represented different ice flow directions and asynchronous trough excavations during multi-phase glacial evolution of the shelf morphology. Our interpretation of different palaeo-ice stream flow directions and associated migration of ice divides during phases of maximum glaciation and deglaciation is consistent with these cross-cutting relationships on the northeastern shelf (Fig. 10). Collectively, these offshore and onshore data imply that ice-flow directions changed and ice divides migrated significantly during a transition from maximum glaciation to deglaciation due to ice sheet thinning and progressively increased control by underlying topography, as has been described also from larger Pleistocene ice sheets (e.g. McMartin and Henderson, 2004; Hodder et al., 2016). This transition possibly involved competition for ice discharge between the two ice streams on the northeastern shelf and associated piracy of ice drainage basins, which ultimately controlled the switching of ice flow – a mechanism well-known from the marine-based margins of the Laurentide, the Greenland, the British-Irish, and the West Antarctic ice sheets (e.g. Greenwood and Clark, 2009b; Graham et al., 2010; Brouard and Lajeunesse, 2019).

It is difficult to estimate how much thinning or retreat was required for the ice flow to become topographically controlled, but the Vopnafjörður flow-set and its cross cutting of the Bakkaheiði flow-set demonstrate that topographic control on the ice flow was established before the ice sheet margin retreated up from the troughs and onto land. Estimating the absolute timing of this transition is challenging without chronological data. However, data from the western and northern Iceland shelf, as well as from W- and NE-Iceland suggest that the IIS margin was positioned at the mid-shelf from 18.2 to as late as 15.3 ka BP but had lost a substantial part of its volume and retreated rapidly to a position inside the present coast around 14.6 ka BP (Andrews et al., 2000; Eiríksson et al., 2000; Jennings et al., 2000; Norðdahl and Pétursson, 2005; Norðdahl and Ingólfsson, 2015; Patton et al., 2017; Benediktsson et al., in press). Therefore, it is likely that topographic influence on palaeo-ice streaming in NE-Iceland was established between ca. 18 and 16 ka BP, and certainly before 14.6 ka BP. According to Norðdahl and Ingólfsson (2015), the extremely rapid retreat between 15.3 and 14.6 ka BP caused a draw-down of the ice-sheet surface and acceleration of ice flow within ice streams. It may thus be speculated if the SSBs of the younger flow-sets in our study area, e.g. in Vopnafjörður and Bakkaflói, are the result of increased ice-flow velocities during this phase in the deglaciation of the IIS. This also bears on the overall influence of ice streams on the IIS and if/how it progressively decreased during the deglaciation, as has been shown for large Pleistocene ice sheets (Margold et al., 2015; Stokes et al., 2016).

5.4 Implications for reconstructions of the Iceland Ice Sheet

The glacial geomorphology and chronology of sediments and bedforms on the western, north-western, and northern Iceland shelf indicates that the IIS extended to the shelf edge during the LGM (e.g. Syvitski et al., 1999; Norðdahl and Pétursson, 2005; Andrews et al., 2008; Benediktsson et al., 2021b). Unfortunately, similar data is largely absent from the north-eastern, eastern, and southern shelf of Iceland, which hampers reliable reconstructions of palaeo-ice streaming and ice sheet extent (Benediktsson et al., 2021b). Thermomechanical modelling experiments suggest that the IIS culminated at the shelf edge around 22.9 ka BP and was characterized by an E-W orientated central ice divide and topographically controlled ice streams (Patton et al., 2017). This broadly corresponds to onshore and offshore records. Our reconstruction of palaeo-ice streams in NE-Iceland and correlation with offshore troughs incised in a NNE direction (Clark and Spagnolo, 2016) supports the presence of an E-W ice divide and an overall northward ice flow in this region. This also implies that ice streaming may have originated in onset zones near the present Vatnajökull ice cap and extended to the northern shelf during maximum glaciation. This region should be mapped in detail in order to test this hypothesis, but it must be acknowledged, however, that onset zones of large ice streams are often rarely preserved because of landscape reshaping during prolonged deglaciation (De Angelis and Kleman, 2008). In contrast, the cross-cutting flow-sets in Bakkaflói and Vopnafjörður suggest that the ice sheet drainage occurred primarily through topographically controlled ice streams during deglaciation, and that onset zones may have shifted as ice divides migrated. These ice streams probably deglaciated rapidly during the collapse of the IIS in the Bølling/Allerød interstadial (Norðdahl and Ingólfsson, 2015), which may explain the preservation of their geomorphological record. However, they may also have been reactivated during Younger Dryas and Preboreal readvances, which terminated several kilometres inland from the present coast (Norðdahl and Hjort, 1993; Sæmundsson, 1995; Norðdahl and Pétursson, 2005; Norðdahl et al., 2019). Based on existing geomorphological and chronological data, it cannot be excluded that the geomorphological imprint of palaeo-ice streaming in our study areas of NE-Iceland results to some degree from the latest regional advances.

While palaeo-ice streams in NW-Iceland appear to have merged on the shelf to feed a larger ice stream that extended to the shelf edge (Principato et al., 2016), our data indicate that each palaeo-ice stream in NE-Iceland drained into its own trough on the shelf. The orientation, dimensions, and extension of these troughs on the NE-Iceland shelf (Spagnolo and Clark, 2009) suggest that these palaeo-ice streams were strong enough to propagate from the shelf break all the way to the ice sheet's interior ice divide . This may also have implications for our notions of turnover rates of the IIS through a glaciation. Future modelling efforts could possibly shed light on the catchment size required to support this kind of ice streaming to the shelf edge and if that corresponds to our empirical geomorphological data and interpretations of the configuration of palaeo-ice streams and location of ice divides.

6. Conclusion

In our study area in NE-Iceland, a total of 797 streamlined subglacial bedforms (SSBs) have been mapped and their orientation and morphometrics measured. The dataset suggests that the SSBs represent the flow-sets of several cross-cutting palaeo-ice streams that drained the north-eastern sector of the Iceland Ice Sheet. Our main conclusions are as follows:

- The majority of the SSBs classify as drumlins (96%). The remaining bedforms are mega-scale glacial lineations (elongation ratio >1:10), which commonly, albeit not exclusively, occur in areas where bedrock strata with a strike sub-paralleling former ice flow frequently crop out on the surface in the form of low, elongate bedrock ridges.
- The distribution and orientation of the SSBs indicate the flow-sets of palaeo-ice streams and the location of ice divides; both of which migrated over time. Thus, the flow-sets are partly asynchronous and overlap in some areas.
- The density and packing of the SSBs possibly suggests that the Bakkaheiði plateau and the Bustarfell-Tunguheiði drumlin field operated as axial zones of ice streaming during maximum glaciation and deglaciation, respectively.

- During maximum glaciation and ice sheet thickness (~1500-200 m), an E-W orientated ice divide was located to the south of the study area promoting ice flow to the north across NE-trending fjords and valleys. Ice flow during this stage was thus independent of underlying topography. This northward ice flow is evident from S-N orientated SSBs within the Bakkaheiði, Þistilfjörður and Jökuldalsheiði flow-sets, and correlates with a NNE-trending shallow trough offshore.
- During deglaciation, probably between c. 18.2 and 14.6 ka BP, ice flow became progressively more controlled by topography due to ice thinning. Palaeo-ice streams flowed along valleys and fjords towards the north (in Þistilfjörður) and northeast (in Bakkaflói and Vopnafjörður), generating younger flow-sets that crosscut the older ones. This is evident from the Bakkaheiði plateau and the eastern margin of the Þistilfjörður area and corresponds to the NE-trending Bakkaflói trough that crosscuts the older and shallower trough trending NNE.
- Acceleration of topographic ice streams, induced by ice shelf collapse and extremely rapid retreat between c. 15.3 and 14.6 ka BP, may have generated the well-preserved drumlin fields in the axial zones of the younger palaeo-ice stream flow-sets.
- The exact age of these flow-sets is uncertain, but it must be considered most likely that the older flow-sets pertain to the LGM and the younger flow-sets to the following deglaciation. However, this inference must be tested with future research.

The results of this study demonstrate the importance of glacial geomorphological mapping for the reconstruction of palaeo-ice streams and ice divides for understanding the evolution of the IIS. This study increases our understanding of the dynamics of the IIS and provides analogues to other palaeo-ice streams within the IIS as well as guiding future efforts towards constraining the evolution of shelf glaciation and the chronology of ice stream retreat.

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Table caption

Table 1. Morphometrics of streamlined subglacial bedforms in NE-Iceland.

Figure caption

Figure 1. (A) Iceland with a bathymetric DEM of the Iceland shelf. Bathymetry from GEBCO. Arrows indicate previously hypothesized major ice streams according to Bourgeois et al. (2000), Stokes and Clark (2001), and Principato et al. (2016). Black and white arrows on the north-eastern shelf indicate cross-cutting troughs identified by Clark and Spagnolo (2016). (B) Glacial geomorphology of the Iceland continental shelf based on Spagnolo and Clark (2009) and Patton et al. (2017). The blue polygons indicate terrestrial palaeo-ice stream flow sets in N- and NE-Iceland as outlined by Patton et al. (2017). Modified from Patton et al. (2017). The red box in A and B indicates the study area (Figure 2).

Figure 2. (A) Overview map of streamlined subglacial bedforms and glacial lineations in NE-Iceland. The white dashed lines indicate boundaries between the study areas of Þistilfjörður, Bakkaflói, Bakkaheiði, and Vopnafjörður-Jökuldalsheiði. The locations of figures 3-6 are indicated with black squares. Map base layer: Hillshade of the ArcticDEM (Porter et al., 2018). (B) Altitudinal distribution of streamlined subglacial bedforms. The inset histogram shows that 15% of all bedforms occur below 200 m a.s.l. but that 79% are situated at 200-600 m a.s.l.

Figure 3. (A) Streamlined subglacial bedforms and glacial lineations in the Þistilfjörður subarea. See Fig. 2 for location. Rose diagram indicates the orientation of the bedforms. Location of bedforms shown on B-D is indicated. (B) Example of a segmented MSGL with inset long (X-X’) and cross (Y-Y’) terrain profiles. Contour lines are 5m. (C-D) Downglacier and upglacier view along the MSGL in B.

Figure 4. Overview of the transistion zone between the Þistilfjörður and Bakkaflói areas showing cross-cutting ice flow indicators. N-S orientated and SW-NE orientated streamlined subglacial bedforms and lineations and reconstructed ice flow are indicated in black and white, respectively. Ovals indicate mapped SSBs, and solid and dashed lines indicated mapped glacial lineations. The N-S streamlining on the western (Þistilfjörður) side appears to be superimposed by the SW-NE streamlining on the eastern (Bakkaflói) side.

Figure 5. (A) Streamlined subglacial bedforms and glacial lineations in the Bakkaflói and Bakkaheiði subareas. See Fig. 2 for location. Rose diagrams indicate SSBs orientation. Location of bedforms shown on B and D is indicated. (B) An example of a SSB on Bakkaheiði with long (X-X') and cross (Y-Y') terrain profiles indicated by blue dashed lines. Contour lines are 5m. (C) A panorama view of the SSB shown in B with black, dashed line outlining the bedform surface profile. (D) Terrain long and cross profiles of the bedform shown in B and C. (E) Example of a SSB in the Bakkaflói area. Long (X-X') and cross (Y-Y') terrain profiles indicated by blue dashed lines and shown on the inset diagram. Contour lines are 5m. (F) Down-ice view along the subtle bedform shown in E. Persons for scale encircled.

Figure 6. (A) Streamlined subglacial bedforms and glacial lineations in the Vopnafjörður-Jökuldalsheiði area. Rose diagram shows their orientation. The Bustarfell drumlin field is encircled. (B) Drumlin Thury as an example of a drumlin within the Bustarfell drumlin field. Blue dashed lines indicate the long (X-X') and cross (Y-Y') profiles shown on the inset. Contour lines are 5m. Overview photograph of drumlin Thury from the viewpoint (yellow star) indicated on B. Note the two transverse channels that cut across the drumlin. (D) Ground view from a SSB on Tunguheiði. (E and F) Drumlins within the Bustarfell drumlin field where ice flow was towards the northeast (white arrows). Note the car (black arrow) for scale on E. Dashed lines on F indicate the long axes of the most obvious drumlins in this view.

Figure 7. Size-frequency distribution of the morphometrics of the streamlined subglacial bedforms presented with histograms and boxplots. A) Length. B) Width. C) Elongation ratio. The median and average of the datasets are denoted by the horizontal line and the ‘x’, respectively, within the box plots. Half (50%) of the values occur within the boxes and the other half outside. The dots are outliers.

Figure 8. Relationships between SSB length and width (A), length and elongation ratio (B), and width and elongation ratio (C). Values within the 90th percentile are represented by gray circles and the remaining 10% by orange squares.

Figure 9. A) Density of SSBs per 4 km2. B) Packing of SSBs per 4 km2.

Figure 10. Hypothesized flow sets of cross-cutting palaeo-ice streams in NE-Iceland. A) Flow-sets related to a maximum phase of glaciation during which ice flow was predominantly towards north independent of underlying topography. A major E-W orientated ice divide was located near or above the present Vatnajökull ice cap (south of this map; see Fig. 1). This northward ice flow corresponds to a NNE trending shallow trough on the shelf. B) Flow-sets related to deglaciation when the ice sheet had become thinner and ice streams were topographically controlled. A major ice divide was located above the mountain range to the west of the study area and in the highland area between Þistilfjörður and Vopnafjörður. Converging palaeo-ice stream flow characterized the areas of Jökuldalsheiði-Vopnafjörður, Bakkaflói, and Þistilfjörður. This convergent flow pattern suggests the onset zones of ice streaming and implies that the trunk flow zones were mainly located within troughs on the shelf (indicated by dashed, blue arrows; described by Spagnolo and Clark, 2009). Note the cross-cutting of the older NNE-trending trough (on A) by the younger NE-trending trough, as identified by Clark and Spagnolo (2016).

Table 1

		Þistilfjörður	Bakkaflói	Bakkaheiði	Vopnafjörður-Jökuldalsheiði	All
n		164	77	246	310	797
Length (m)	Median	576	451	530	749	623
	Mean	717	501	649	827	719
	Max	2694	1095	3841	2905	3841
	Min	101	135	154	200	101
	10%	219	292	265	387	291
	90%	1322	799	1120	1345	1253
	Stdew	495	210	426	423	442
Width (m)	Median	151	154	147	192	163
	Mean	179	167	161	208	185
	Max	942	347	459	666	942
	Min	36	61	51	43	36
	10%	72	92	88	108	86
	90%	309	253	262	315	299
	Stdew	136	67	72	96	104
E.R.	Median	3.2	2.9	3.6	3.7	3.5
	Mean	4.4	3.1	4	4.1	4.0
	Max	16.8	8.3	14.4	12.8	16.8
	Min	1.9	1.9	2	1.9	1.9
	10%	2.4	2.3	2.5	2.8	2.5
	90%	8.0	4.1	5.6	6.0	5.9
	Stdew	2.8	1.1	1.9	1.7	2
Orientation(°)		23	35	6	38	-
Area (km^2)		1400	550	500	2300	2300
MSGLs		12	0	9	11	32

Declaration of competing interest

The authors declare no conflict of interests

Highlights

- Streamlined subglacial bedforms reveal palaeo-ice streams flow-sets in NE-Iceland.
- The flow-sets reflect shifts in ice sheet dynamics and migration of ice divides.
- Ice streaming during maximum glaciation was towards north from an E-W ice divide.
- Topographic ice streams emanated from a N-S and E-W ice divide during deglaciation.
- Well-developed drumlin fields likely formed under ice streams during deglaciation.

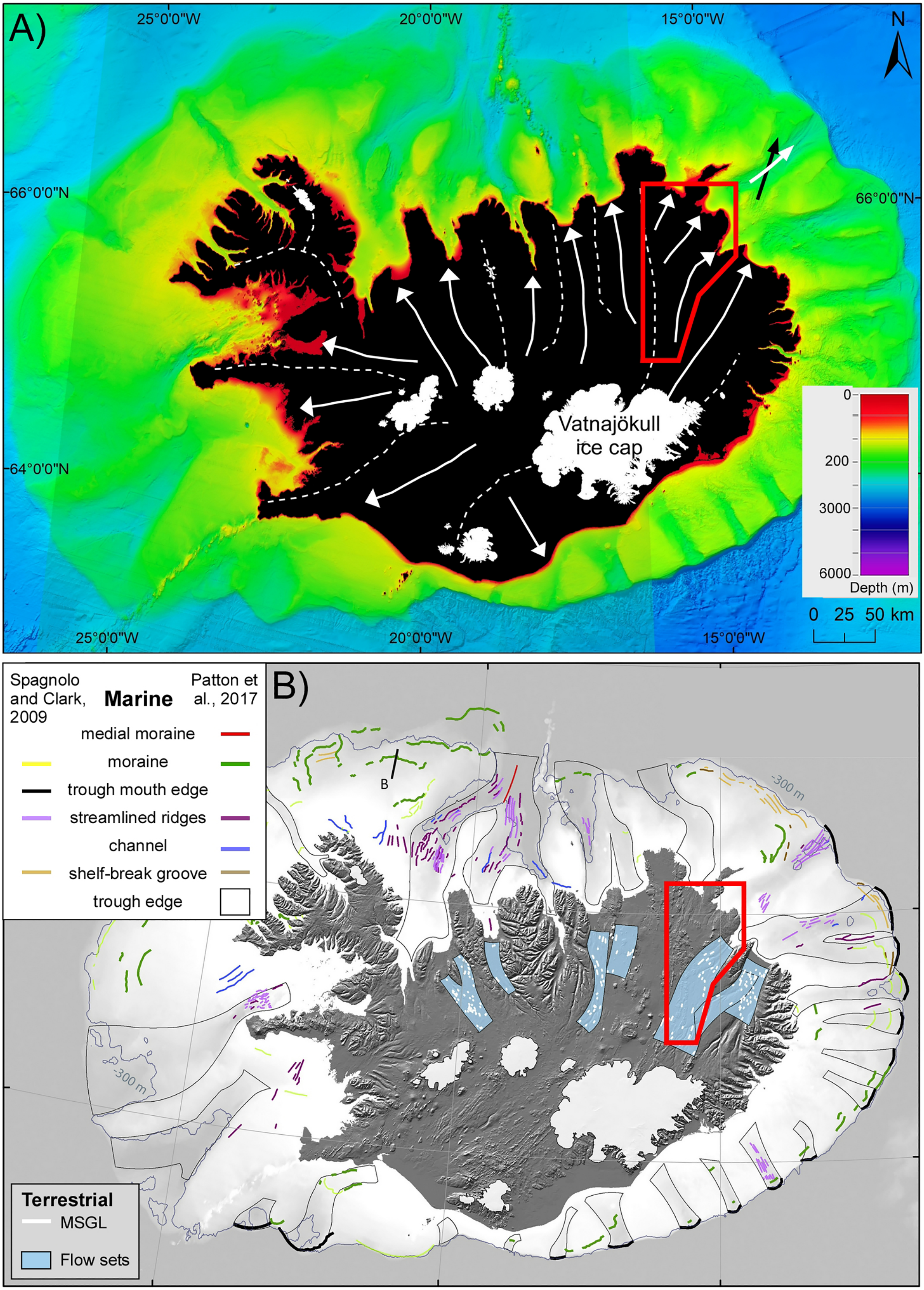

A)
25°0'0"W
20°0'0"W
15°0'0"W
N
66°0'0"N
66°0'0"N
64°0'0"N
Vatnajökull ice cap
0
200
3000
6000
Depth (m)
0 25 50 km
25°0'0"W
20°0'0"W
15°0'0"W
B)
Spagnolo and Clark, 2009
Marine
Patton et al., 2017
medial moraine
moraine
trough mouth edge
streamlined ridges
channel
shelf-break groove
trough edge
B
-300 m
-300 m
Terrestrial
MSGL
Flow sets

Figure 1

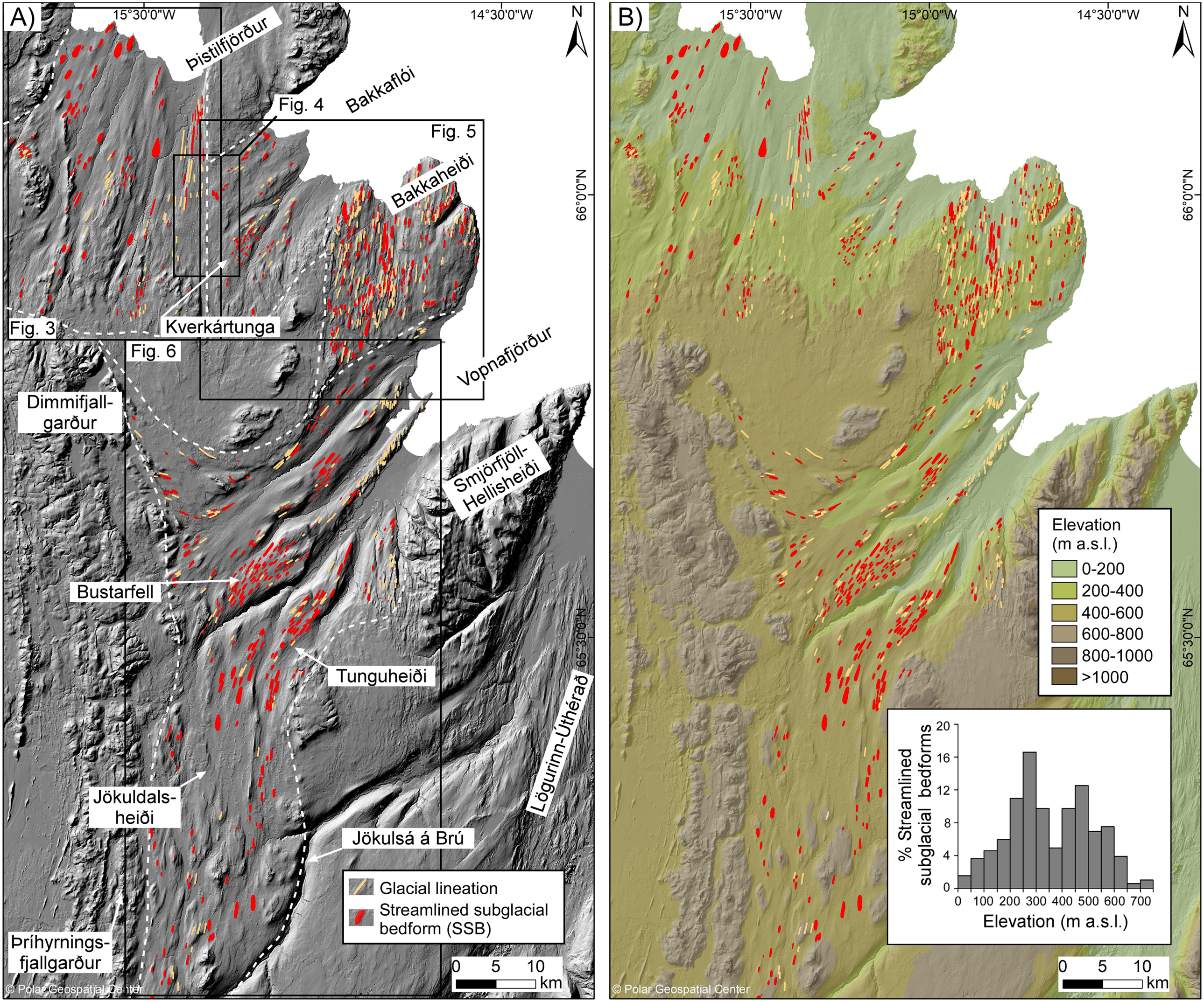
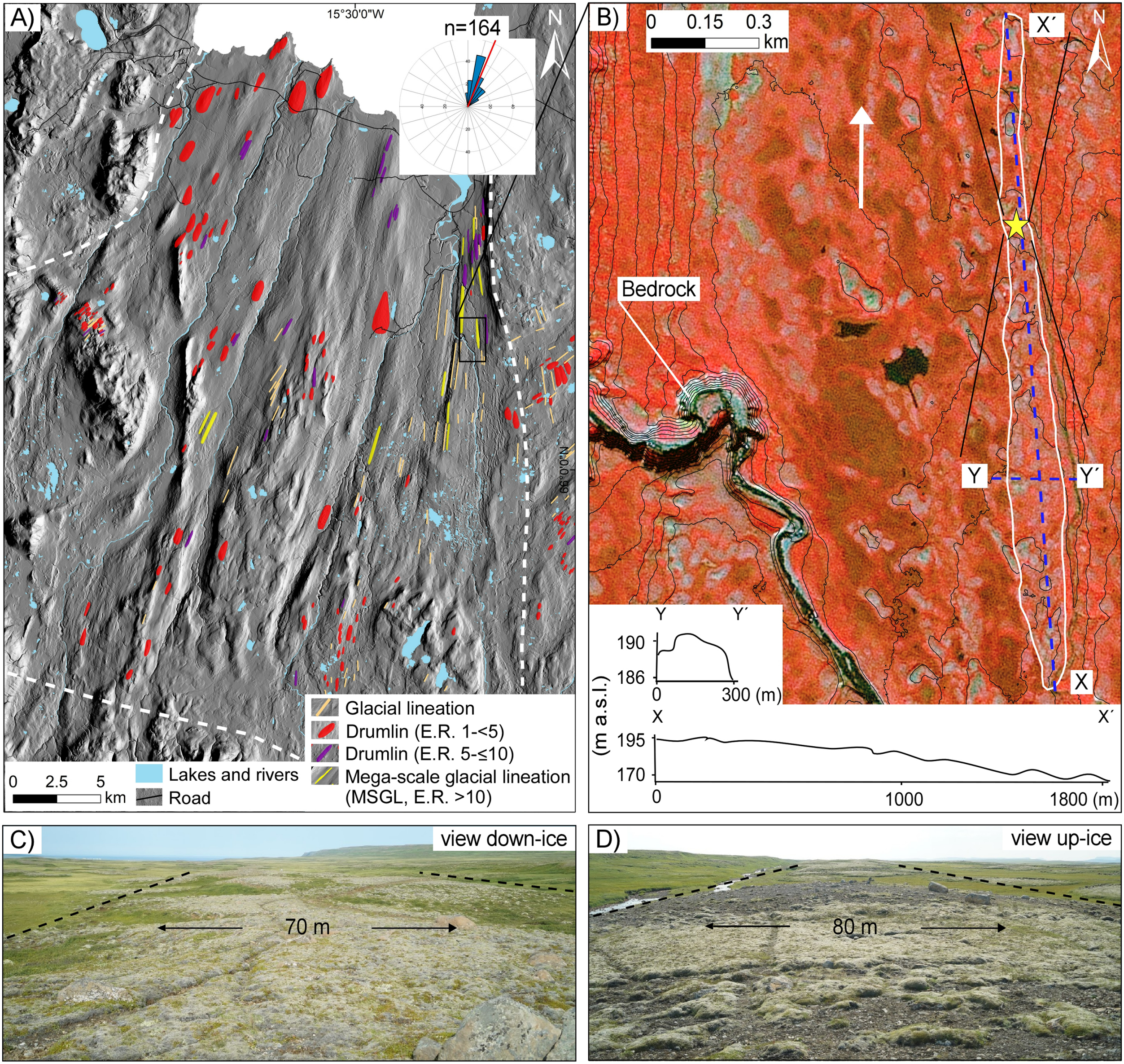

A)
15°30'0"W
15°0'0"W
14°30'0"W
N
Þistilfjörður
Bakkaflói
Fig. 4
Fig. 5
Bakkaheiði
66°0'0"N
Fig. 3
Kverkártunga
Fig. 6
Vopnafjörður
Dimmifjall-garður
Smjörfjöll-Hellisheiði
Bustarfell
65°30'0"N
Tunguheiði
Lögurinn-Úthérað
Jökuldals-heiði
Jökulsá á Brú
Glacial lineation
Streamlined subglacial bedform (SSB)
Þríhyrnings-fjallgarður
0 5 10 km
© Polar Geospatial Center
B)
15°30'0"W
15°0'0"W
14°30'0"W
N
66°0'0"N
65°30'0"N
Elevation (m a.s.l.)
0-200
200-400
400-600
600-800
800-1000
>1000
% Streamlined subglacial bedforms
0
4
8
12
16
20
0 100 200 300 400 500 600 700
Elevation (m a.s.l.)
0 5 10 km
© Polar Geospatial Center

Figure 2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15°30'0"W
n=164
N
66°0'0"N
Glacial lineation
Drumlin (E.R. 1-<5)
Drumlin (E.R. 5-≤10)
Mega-scale glacial lineation (MSGL, E.R. >10)
Lakes and rivers
Road
0 2.5 5 km
B)
0 0.15 0.3 km
N
X′
Bedrock
Y
Y′
X
Y Y′
190
186
0 300 (m)
(m a.s.l.)
X X′
195
170
0 1000 1800 (m)
C)
view down-ice
70 m
D)
view up-ice
80 m

Figure 3

Figure 4

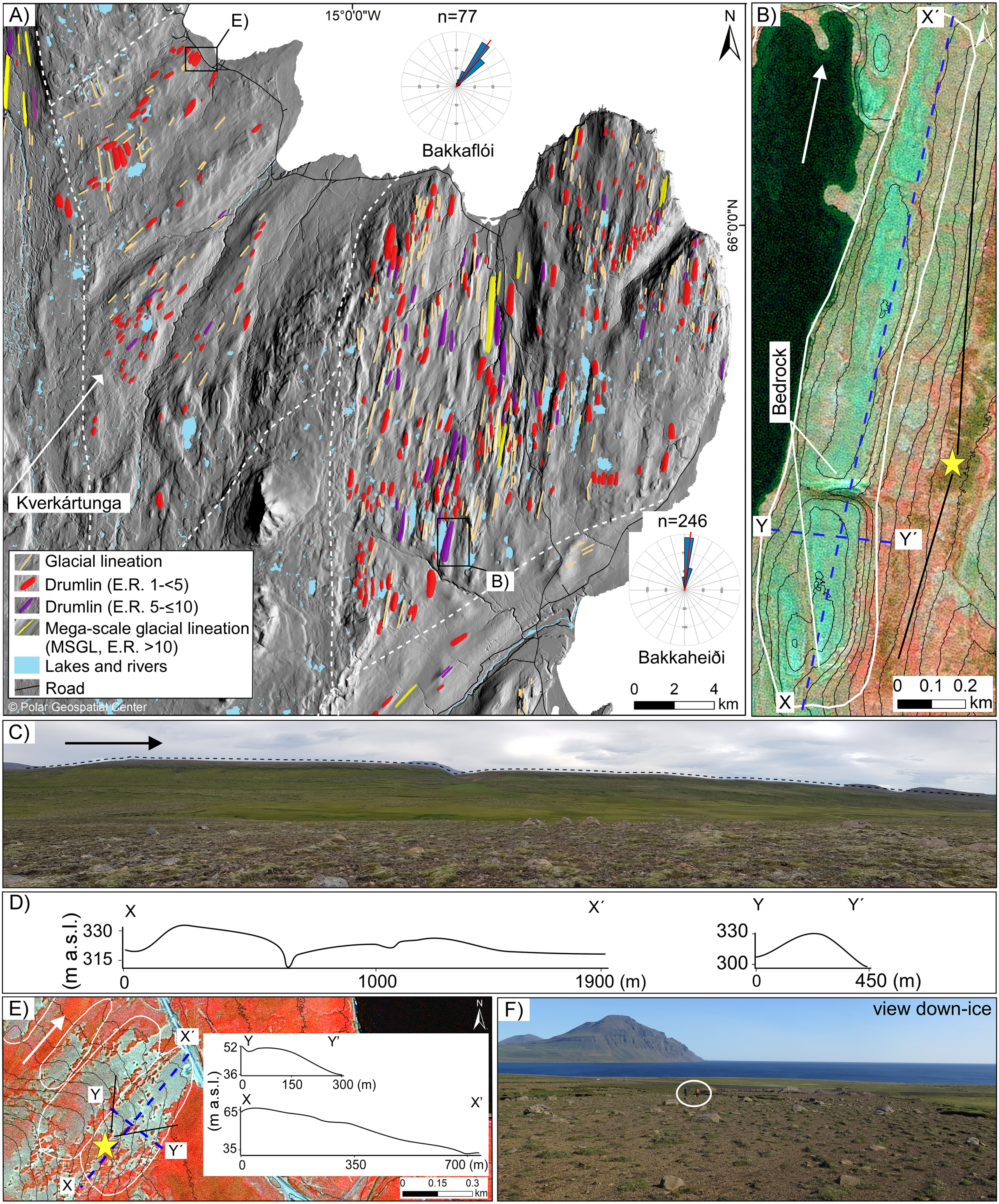
A)
E)
15°0'0"W
n=77
Bakkaflói
N
66°0'0"N
Kverkártunga
n=246
Bakkaheiði
B)
Glacial lineation
Drumlin (E.R. 1-<5)
Drumlin (E.R. 5-≤10)
Mega-scale glacial lineation (MSGL, E.R. >10)
Lakes and rivers
Road
© Polar Geospatial Center
0 2 4 km
B)
X´
N
Bedrock
Y
Y´
X
0 0.1 0.2 km
C)
D)
X
X´
(m a.s.l.)
330
315
0
1000
1900 (m)
Y
Y´
330
300
0
450 (m)
E)
X´
Y
Y´
X
N
Y
Y´
52
36
0
150
300 (m)
(m a.s.l.)
X
X´
65
35
0
350
700 (m)
0 0.15 0.3 km
F)
view down-ice

Figure 5

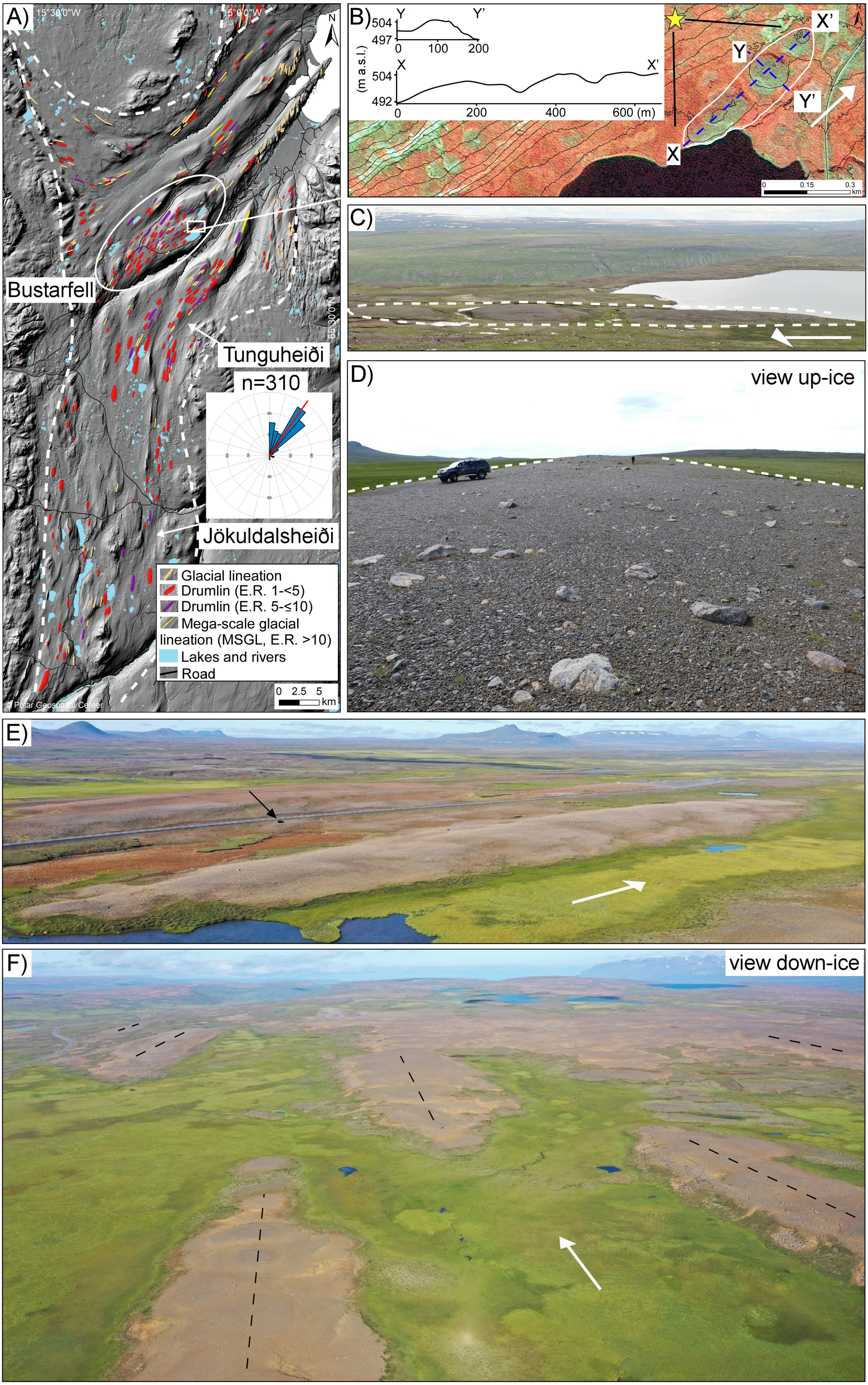
A)
15°30'0"W
15°0'0"W
N
65°30'0"N
Bustarfell
Tunguheiði
n=310
Jökuldalsheiði
Glacial lineation
Drumlin (E.R. 1-<5)
Drumlin (E.R. 5-≤10)
Mega-scale glacial lineation (MSGL, E.R. >10)
Lakes and rivers
Road
0 2.5 5 km
© Polar Geospatial Center
B)
Y Y'
504
497
0 100 200
(m a.s.l.)
X X'
504
492
0 200 400 600 (m)
X'
Y
Y'
X
N
0 0.15 0.3 km
C)
D)
view up-ice
E)
F)
view down-ice

Figure 6

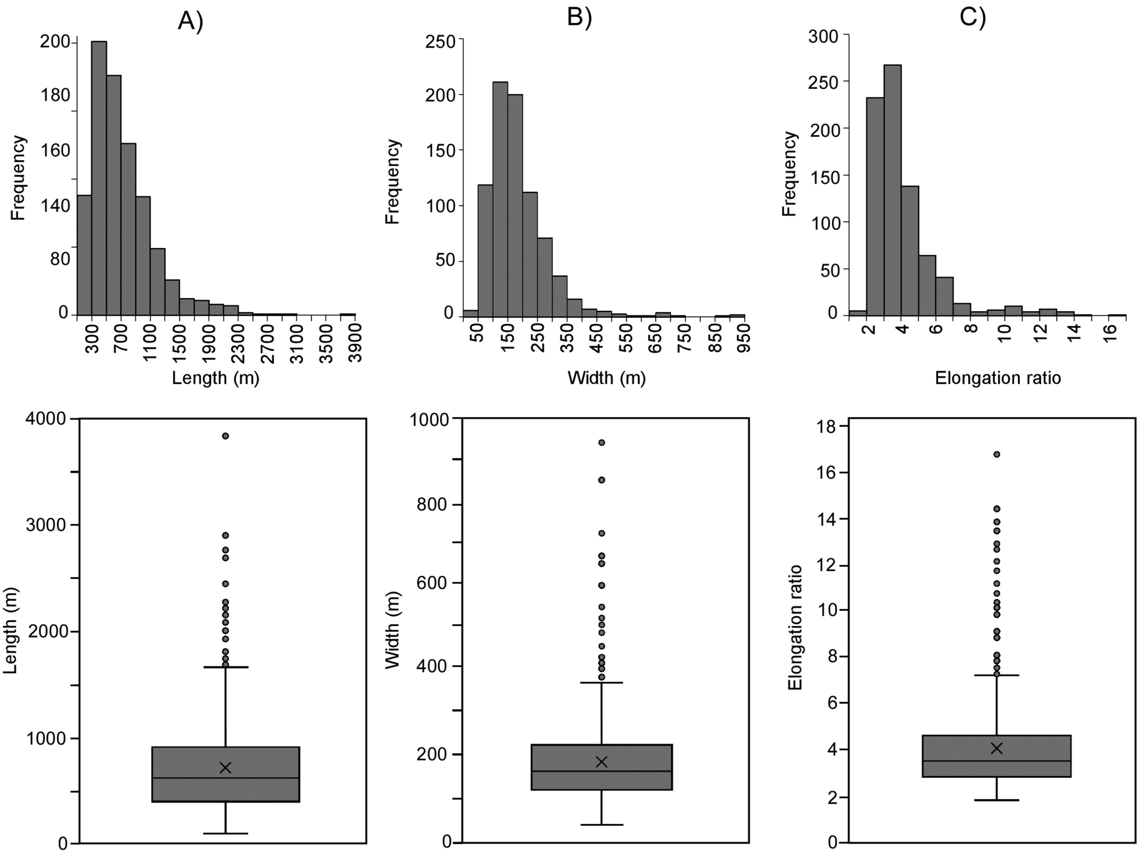
A)
200
180
160
140
80
0
Frequency
300
700
1100
1500
1900
2300
2700
3100
3500
3900
Length (m)
B)
250
200
150
100
50
0
Frequency
50
150
250
350
450
550
650
750
850
950
Width (m)
C)
300
250
200
150
100
50
0
Frequency
2
4
6
8
10
12
14
16
Elongation ratio
4000
3000
2000
1000
0
Length (m)
1000
800
600
400
200
0
Width (m)
18
16
14
12
10
8
6
4
2
0
Elongation ratio

Figure 7

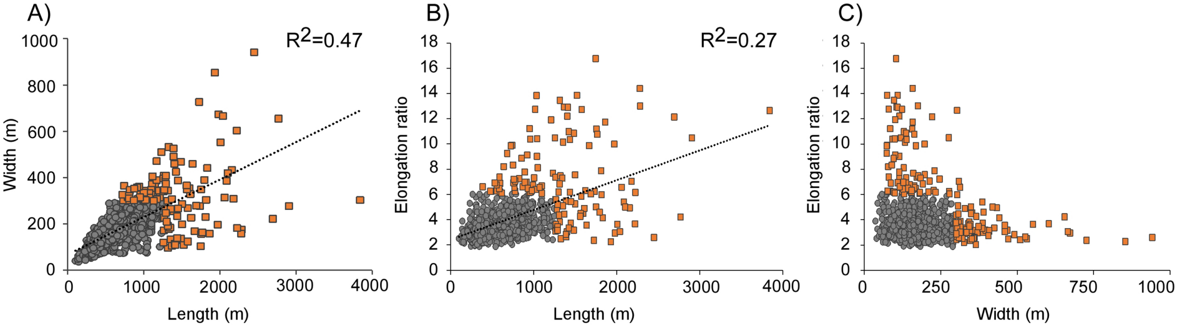
A)
R²=0.47
Width (m)
1000
800
600
400
200
0
0
1000
2000
3000
4000
Length (m)
B)
R²=0.27
Elongation ratio
18
16
14
12
10
8
6
4
2
0
0
1000
2000
3000
4000
Length (m)
C)
Elongation ratio
18
16
14
12
10
8
6
4
2
0
0
250
500
750
1000
Width (m)

Figure 8

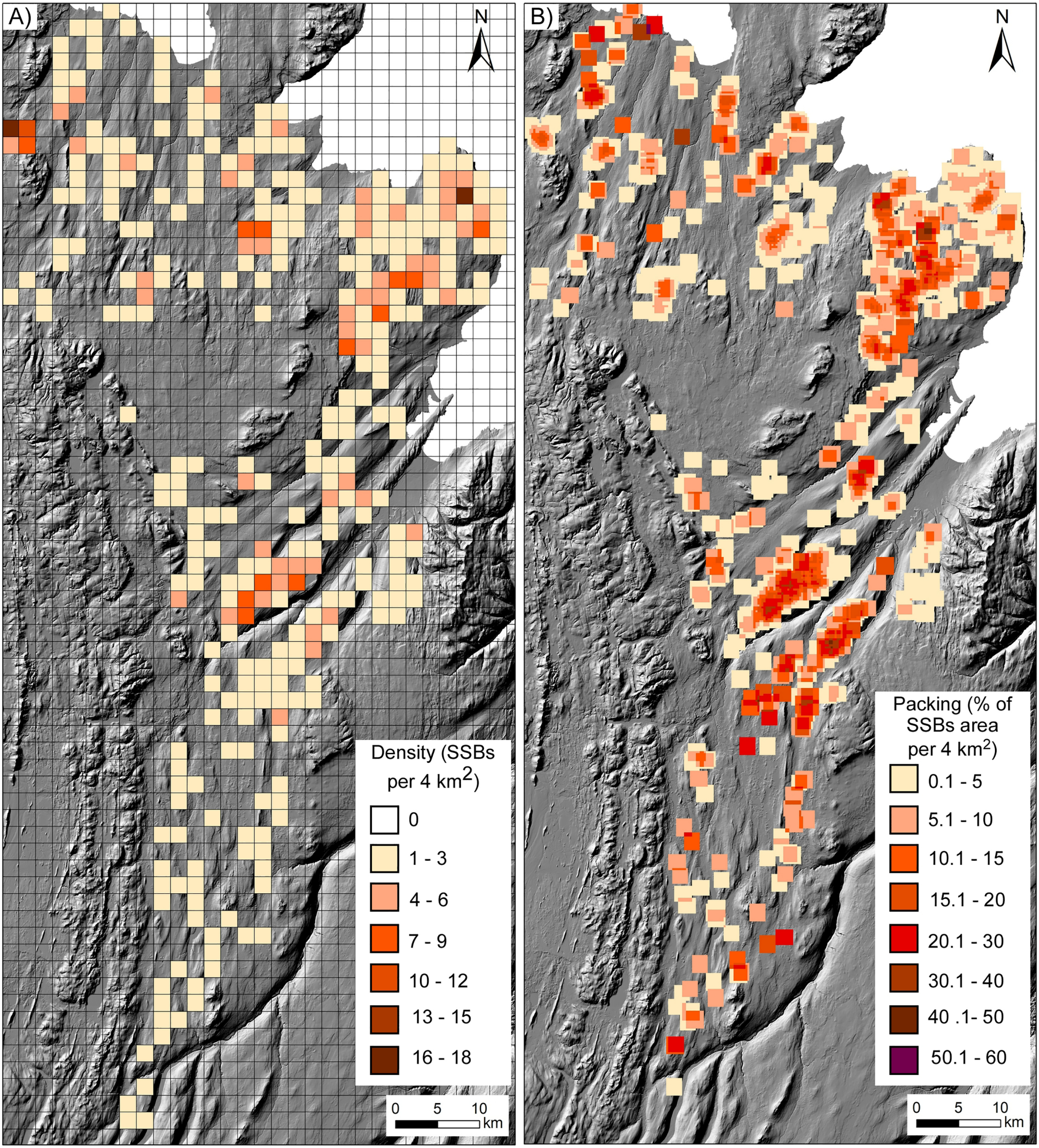
A)
N
Density (SSBs per 4 km^2)
0
1 - 3
4 - 6
7 - 9
10 - 12
13 - 15
16 - 18
0 5 10 km
B)
N
Packing (% of SSBs area per 4 km^2)
0.1 - 5
5.1 - 10
10.1 - 15
15.1 - 20
20.1 - 30
30.1 - 40
40 .1- 50
50.1 - 60
0 5 10 km

Figure 9

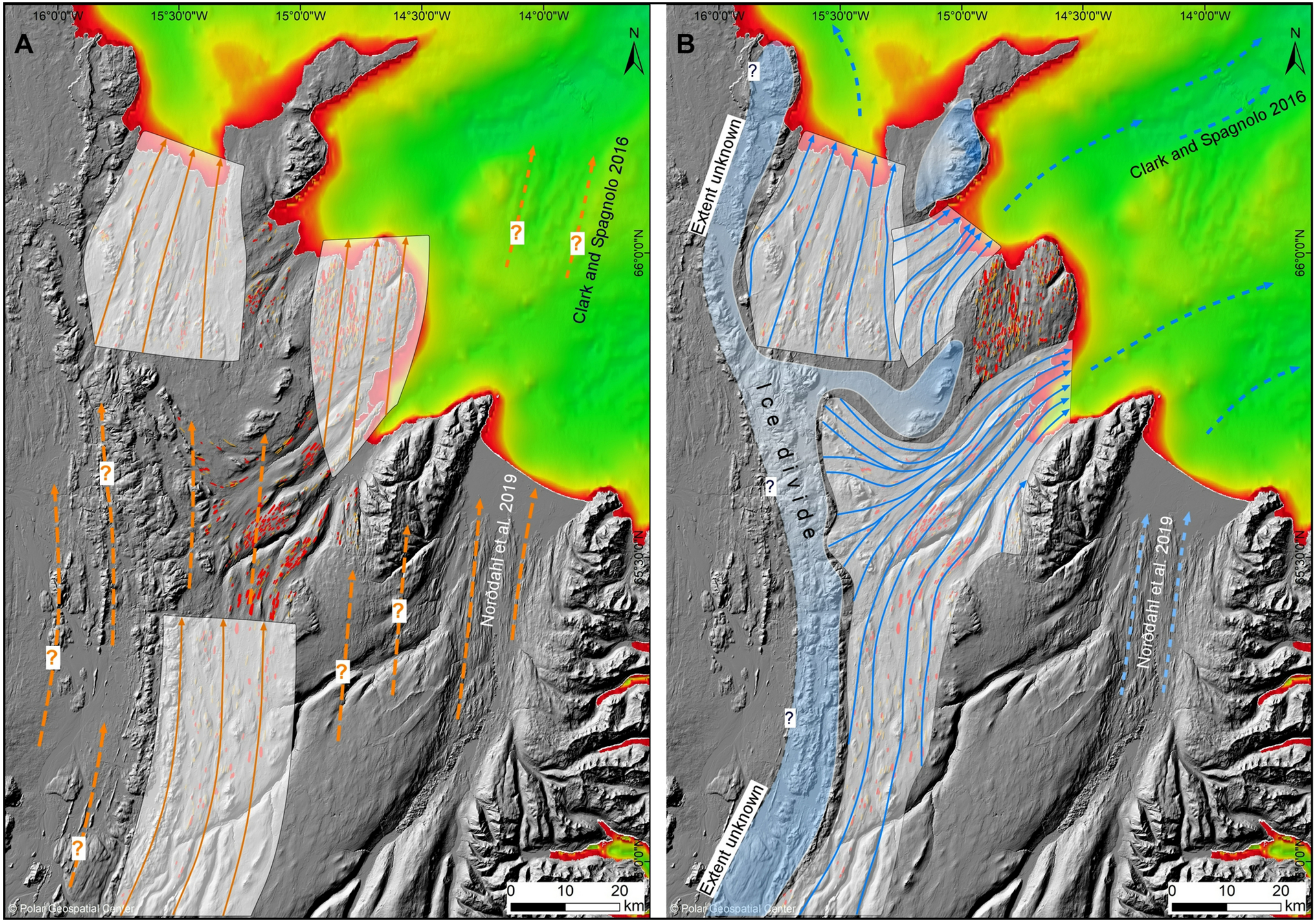
A
B
16°0'0"W
15°30'0"W
15°0'0"W
14°30'0"W
14°0'0"W
66°0'0"N
65°30'0"N
N
Clark and Spagnolo 2016
Norðdahl et al. 2019
?
Extent unknown
Ice divide
Extent unknown
0
10
20
km
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Figure 10